INFLUENCE OF SEEPAGE WATER ON DEFORMATIONAL BEHAVIOR OF PERMEABLE ASPHALT PAVEMENTS

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ABSTRACT
Permeable asphalt pavements are used to reduce stormwater runoff from new developments. However, due to the heavy traffic on roadways, the durability of pavements is of great concern. In this study, cyclic plate loading tests on model pavements that simulate permeable asphalt pavements were carried out. The models were tested under both unsaturated and saturated conditions to investigate the effect of the combination of high saturation and repeated loading on the long-term deformational behavior of permeable asphalt pavements. From the test results, it was confirmed that the permanent deformation in the saturated models was five to six times larger than that of the models with natural water content, regardless of the type of subgrade soil. In the case where the subgrade consisted of cohesive soil, a large plastic deformation in the subgrade was a major cause of the deformational behavior. On the other hand, when the subgrade consisted of sandy soil, the compression of the subbase was a major cause of the deformational behavior, considering the test result that the settlement of the subgrade surface was very small and did not depend on the saturation degree.

1. INTRODUCTION

Permeable asphalt pavement consists of a paved surface and a subbase comprising open-graded asphalt concrete and aggregates, as shown in Figure 1. The pavement allows rainwater to flow through the pavement surface and infiltrate the soil below. Such pavements have been used in parking lots and sidewalks since the mid-1970s to reduce stormwater runoff from new developments. These pavements have been proving their worth and recent changes in stormwater regulations in Japan [1] have prompted us to expand the application of permeable asphalt pavements from lightly loaded areas such as parking lots and sidewalks to heavily trafficked roadways [2].

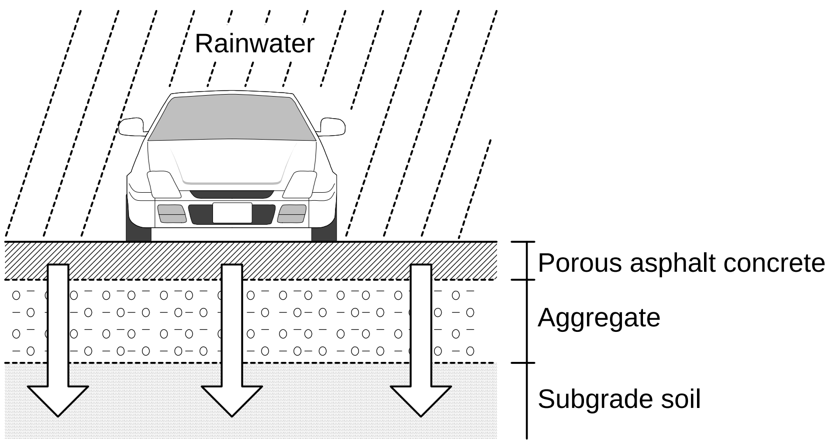


Figure 1 Cross section of a permeable asphalt pavement

Pavement durability is of great concern when permeable asphalt is used to build heavily trafficked roadways. The combination of high saturation due to seepage water and the cyclic loading caused by heavy traffic might have a harmful effect on the strength and stiffness of the subbase and subgrade soils. The saturation degree of most granular materials affects the resiliency and permanent strain response characteristics of the material under laboratory and in situ conditions [3, 4]. Generally, when complete saturation is reached, the deformational behavior may be affected significantly. Researchers [e.g., 5–8] have reported that the resilient modulus decreases with an increase in the saturation level. As the moisture content increases and reaches saturation, a positive pore-water pressure might develop under rapidly applied loads. Excessive pore pressure reduces the effective stress, thereby resulting in a decrease in the resistance to permanent deformation. Many researchers who have studied the effect of water content in granular pavement layers in the laboratory and in the field believe that the combination of a high saturation degree and low permeability due to poor drainage leads to a high pore pressure, low effective stress, low stiffness, and low deformation resistance [5, 8, 9–11]. From these studies, we can expect premature failure of permeable asphalt pavements under heavy traffic if they are designed to have the same thickness as normal or impervious pavements.

Contrary to this expectation, however, premature failure of permeable pavements has not yet been reported in Japan; Ito et al. [12] carried out studies on the permeable pavement roadways in Japan. The thicknesses of all of the pavements in the report were determined by using the CBR-T_A method, which is similar to the method used for designing normal pavements. Based on a follow-up investigation, they stated that in the case of light-traffic roadways, the pavements displayed no notable degradation after several years' service regardless of the type of subgrade soil (cohesive soils and sandy soils). Ito et al. [12] also noted that significant performance degradation had not been confirmed in heavy-traffic roadways even after ten years of service when the subgrade consisted of sandy soil. Despite this report, it is too early to conclude that a permeable pavement is suitable for heavy-traffic roadways or that such permeable-pavement roadways can be designed in the same way as normal pavements; this is because most of the heavy-traffic roadways reported in the study were constructed by taking measures to prevent premature failure. For example, the roadways in the study had thick pavements, installation ofincluded a filter sand layer or geotextile on the subgrade surface, and were installed with drain pipes, etc. Additionally, complete saturation of the pavement might not have occurred due to the low frequency of heavy rains in the study area, thereby preventing the pavements from premature failure. In order to verify the applicability of a permeable asphalt pavement to heavy-traffic roadways and to establish the design method, the long-term deformational characteristics of the pavements under controlled boundary conditions must be examined.

In this study, cyclic plate loading tests are carried out on permeable pavement models under saturated and unsaturated conditions in the laboratory to determine the long-term deformational characteristics of permeable asphalt pavements. The deflection in the pavement surface, earth pressure, and pore-water pressure in the subgrade soil are measured. On the basis of the experimental results, the influences of saturation degree and type of subgrade soil on the deformational behavior of permeable pavements are discussed.

2 OUTLINE OF THE MODEL TESTS

2.1 Permeable pavement model

Figure 2 shows the cross section of the pavement model. The model is cylindrical with a diameter of 1000 mm and a depth of 1000 mm. The diameter of the loading plate (*D*) is 300 mm. The model size was determined by considering the influence area of the applied load. According to the elastic theoretical solution on stress distribution in a semi-infinite soil under uniform circular loading, vertical stress decays to less than 3% of the surface pressure at a depth of 1000 mm (the bottom of the model) and less than 1% at a horizontal distance of 500 mm from the loading axis (the wall of the model). Therefore, we can conclude that the model is considerably large when compared to the influence area of the applied load.

The steel container is composed of 10 steel rings on a steel base tank. The rings were built up by using bolts and nuts and the joints were sealed by using a silicone sealant.

The pavement model comprises a surface course, a base course, a subbase course, a subgrade, and a water supply and drainage layer. The water supply and drainage layer works as a filter to supply water uniformly into the model. Table 1 shows the materials used and the thickness of each layer. The pavement materials used in this study have been generally used for permeable pavements in Japan. The surface course is an open-graded asphalt concrete made by using high-viscosity modified asphalt; the base course consists of asphalt-treated aggregates composed of a polymer-modified

asphalt binder, and the subbase course is a crusher-run.

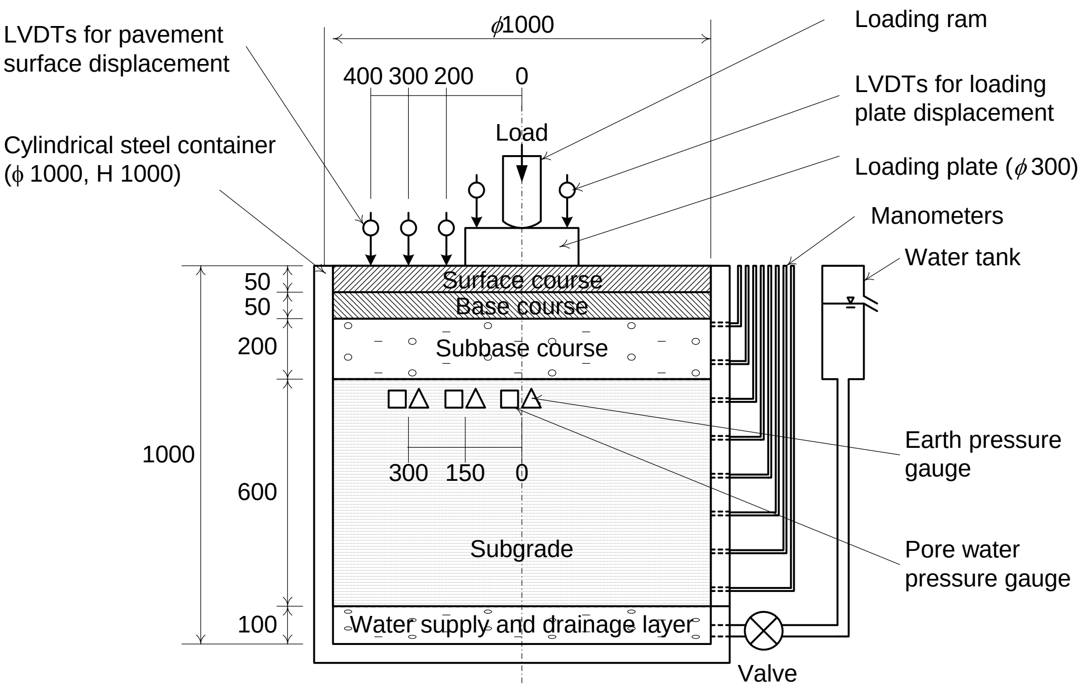


Figure 2 Cross section of the permeable pavement model

Table 1 Materials used and the thicknesses of the model pavements

	Thickness	Material	a_i 1)
Surface course	50 mm	An open-graded asphalt mix with a top diameter of 13 mm prepared by using high-viscosity modified asphalt type-H	1.0
Base course	50 mm	An asphalt-treated aggregate with a top diameter of 30 mm prepared by using polymer-modified asphalt binder type-II	0.8
Subbase course	200 mm	Crusher-run with a top diameter of 40 mm	0.25
Subgrade	600 mm	a) Edosaki sand b) Kasumigaura sand c) Kanto loam	
Drainage layer	100 mm	Aggregate	

1) a_i : an equivalency conversion coefficient

The total thickness of the model pavement is 300 mm (=1.0 *D*). The pavement is designed such that the pressure on the subgrade surface due to plate loading is sufficiently high in order to understand the effect of cyclic loading on the subbase course and on the subgrade soil. According to the elastic theoretical solution, vertical stress at 1.0 *D* under the loading center is about 30% of the applied pressure. The thickness of the surface course and the base course (50 mm) is the minimum thickness possible due to the grain size of the materials.

Based on the empirical structural design method known as the CBR-T_A method in Japan, the

relationship between the total amount of wheel load and the required pavement thickness from the standpoint of fatigue failure is expressed by the following equation [13].

$$T_A = \frac{3.84\, N^{0.16}}{CBR^{0.3}}, \quad (1)$$

where T_A (in cm) is an equivalency conversion thickness that represents the pavement thickness required if the total pavement is constructed with a hot asphalt mix used as a binder and as a surface course; N is the total number of 49-kN equivalent wheel load applications (one wheel per direction) in a specific design period, say 10 years; and *CBR* (in %) is the design CBR of subgrade.

At the same time, T_A', the equivalency conversion thickness of the designed pavement section, is computed as [13]:

$$T_A' = \sum_{i=1}^{n} a_i T_i, \quad (2)$$

where a_i is an equivalency conversion coefficient for each pavement material used and T_i is the thickness of each layer.

The equivalency conversion coefficients for the materials in this study are shown in Table 1 [13, 2]. By using the a_i values and the thickness of each layer, the T_A' value of the pavement model calculated by using equation (2) was found to be 14 cm. By substituting the T_A' value in equation (1), the total number of 49-kN equivalent wheel loads, N, is calculated relative to the value of *CBR*. Figure 3 shows the relationship between N and *CBR*. From the figure, if *CBR* is 2, 10 and 20%, then the total wheel number for fatigue failure, N, is 1.2×10^4, 2.4×10^5, and 9.0×10^5, respectively.

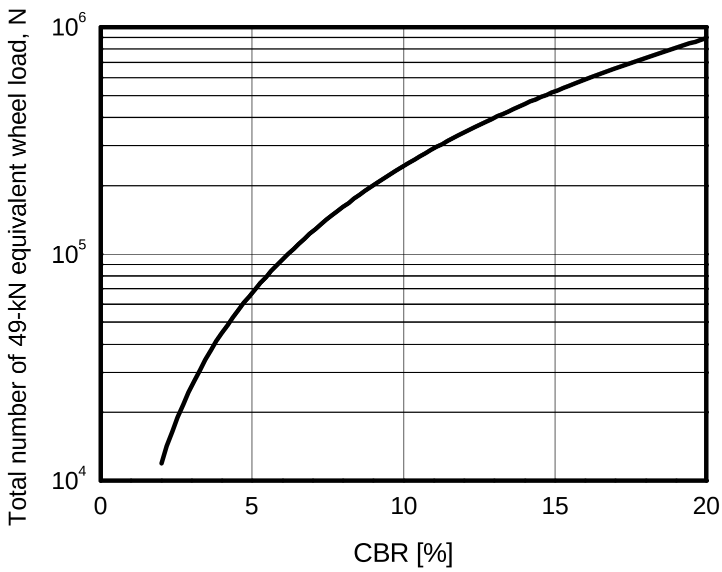


Figure 3 Design number of wheel loads, N, for fatigue failure of asphalt pavement when T_A = 14 cm

Three different soils, Edosaki sand (fine sand), Kasumigaura sand (coarse sand), and Kanto loam (volcanic cohesive soil) were chosen as the subgrade soil material on the basis of their strength, stiffness, and permeability. Figure 4 shows the grading curves of the subgrade soils. The physical and mechanical properties of the subgrade soils are shown in Table 2.

Subgrade and subbase materials were adjusted to their optimum water content and compacted by using a rammer to a compaction ratio of over 95%.

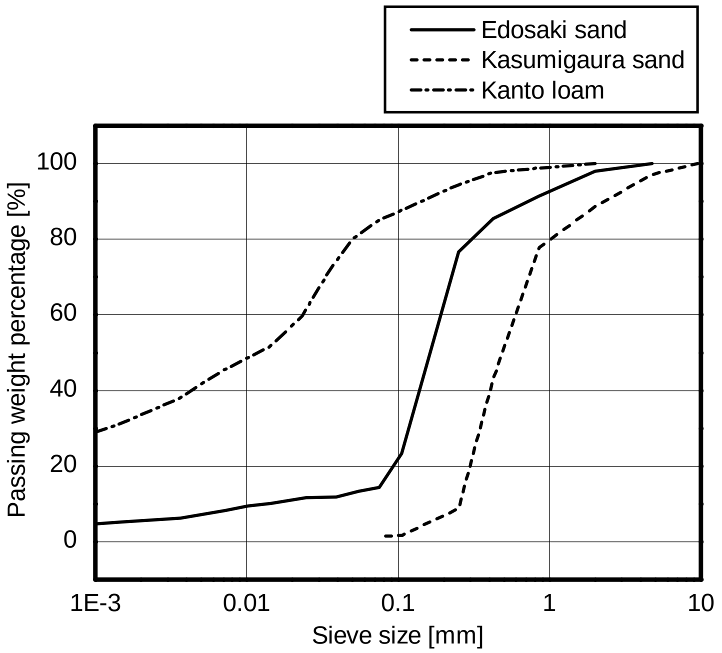


Figure 4 Grain size curves of subgrade soils

Table 2. Physical and mechanical properties of subgrade soils

	Edosaki sand	Kasumigaura sand	Kanto loam
Density of soil particles ρ_s (g/cm^3)	2.689	2.706	2.702
Maximum diameter D_{max} (mm)	4.75	9.50	2.00
60% diameter D_{60} (mm)	0.19	0.57	0.03
10% diameter D_{10} (mm)	0.015	0.255	
Optimum water content w_{opt} (%)	17.0	17.6	72.7
Maximum dry density ρ_{dmax} (g/cm^3)	1.737	1.685	0.850
CBR at laboratory (%)	20	11	2
Hydraulic conductivity k (cm/s)	3.2×10^{-4}	1.8×10^{-2}	3.3×10^{-6}

2.2 Test conditions

The loading conditions are shown in Table 3. Traffic load was simulated by repeated loading at a fixed point by using a rigid steel plate of diameter 300 mm, although recent studies [e.g., 14] have reported that a moving wheel load causes larger plastic deformation in soil when compared to a simple repeated load because of the rotation of the principal stresses. A sine-wave load of 0 to 49 kN was applied at a frequency of 1.0 Hz for a maximum of 10^6 load cycles.

The test cases are shown in Table 4. The experimental parameters were the material of the subgrade soil and the saturation degree. Two models for each subgrade soil were prepared—one model was tested under natural water content (dry model) and the other was tested under saturated conditions (wet model). For the wet model, water was gradually supplied from the base tank by applying a water head difference of about 100 mm; the water level was finally raised to the boundary between the subbase course and the base course. The time for completely saturating the Kasumigaura sand model, Edosaki sand model, and Kanto loam model was one, four, and twelve weeks, respectively. Such complete saturation of the subgrade and subbase courses represents the most severe conditions for pavement durability, although it does not simulate actual saturation phenomena of permeable pavements caused by rainwater.

Table 3. Loading conditions

Loading method	Cyclic plate loading at a constant point
Maximum load	49 kN
Minimum load	0 kN
Waveform	Sine wave (Load control)
Frequency	1.0 Hz
Loading plate	Circular steel plate with a diameter of 300 mm
Number of load cycles	10^6 (maximum)

Table 4. Test cases

Case No.	Material of subgrade soil	Saturated/Unsaturated
Case 1	Edosaki sand	Unsaturated
Case 2	Kasumigaura sand	Unsaturated
Case 3	Kanto loam	Unsaturated
Case 4	Edosaki sand	Saturated
Case 5	Kasumigaura sand	Saturated
Case 6	Kanto loam	Saturated

2.3 Measurements

The applied load was measured by using a load cell, the displacement of the loading plate was measured by using two LVDTs, and the deflection of the pavement surface was measured by using three LVDTs. The earth pressure was measured by using three earth pressure gauges, and the pore water pressure was measured by using three pore water pressure gauges. The positions of the measuring devices are illustrated in Figure 2. All the data were recorded by using a personal computer at a processing speed of 20 Hz.

3 RESULTS OF THE MODEL TESTS

3.1 Wave pattern of measurements

Figure 5 shows the sample wave patterns of the applied load, the deflection of the pavement surface, the earth pressure, and the pore water pressure at the subgrade surface for the Edosaki sand subgrade model. The suffix numbers of D, σ_z, and u represent the distances from the loading axis. From the figure, it can be seen that the measurements oscillate in synchronization with the applied load.

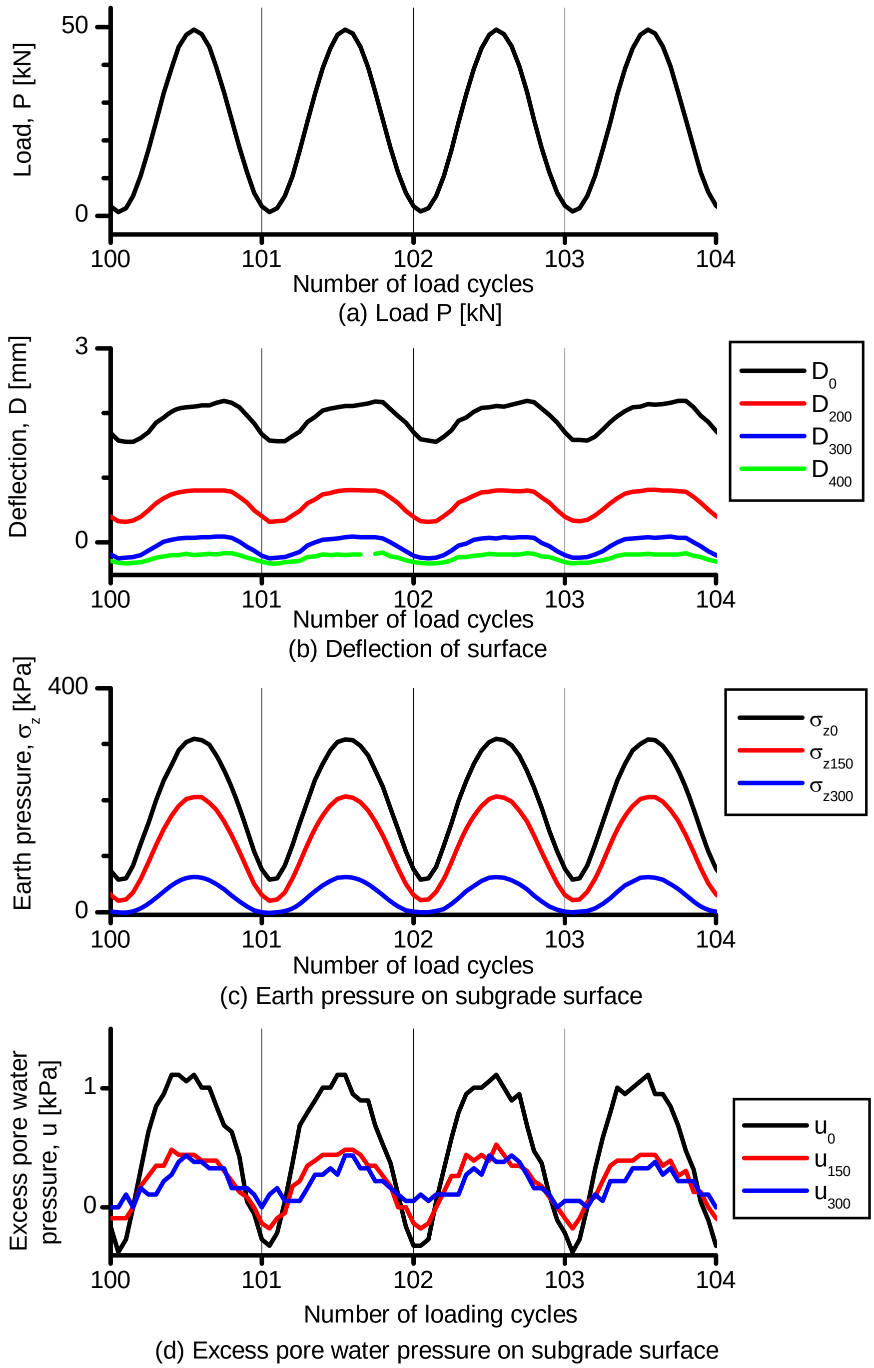


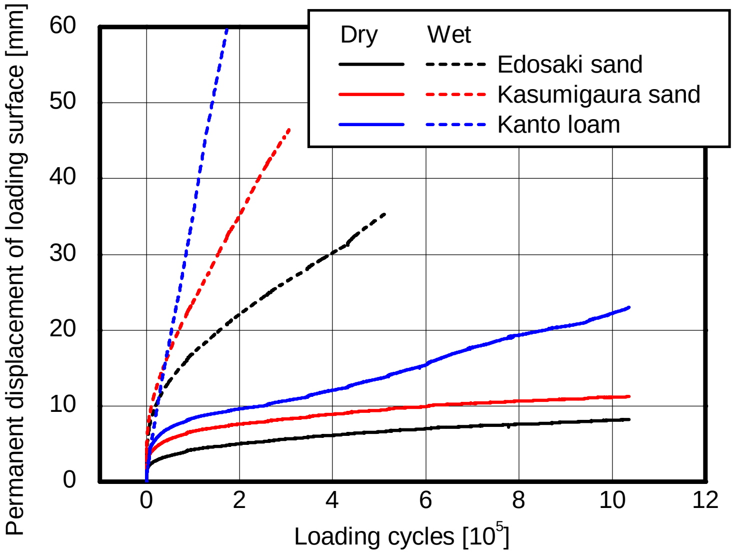
Figure 5 Example wave pattern of measurements (wet Edosaki sand model, N = 100 to 104)

3.2 Permanent and elastic displacement of loading surface

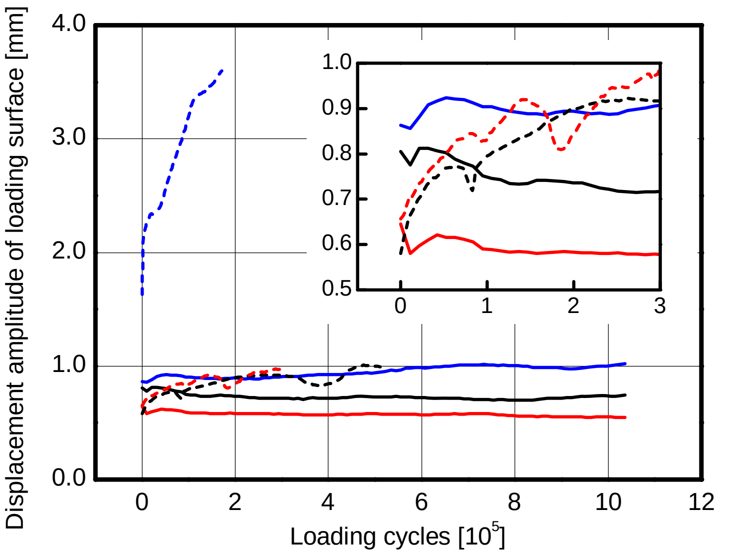
Figure 6(a) shows the change in permanent displacement of the loading surface with the number of loading cycles. The permanent displacement of the wet model increases at five or six times the rate of the dry model, regardless of the type of subgrade soil. This means that complete saturation and repeated loading results in remarkable plastic deformation in the permeable pavements. Regarding differences due to soil type, the degree of permanent displacement is consistent with the *CBR* values presented in Table 2 (Edosaki sand > Kasumigaura sand > Kanto loam), regardless of saturation degree.

The elastic displacement of the loading surface or the displacement amplitude of the loading plate is shown in Figure 6(b). From the figure, only in the case of the wet Kanto loam model, the displacement amplitude increases rapidly with the number of loading cycles. However, the

displacement amplitudes of all the other cases are within the range of 0.5 to 1.0 mm, and the change is very small throughout the test. There is little difference in elastic displacement due to saturation degree in the Edosaki sand and Kasumigaura sand models, although their permanent displacement is significantly affected by saturation degree, as shown in Figure 6(a). This result implies that repeated loading under complete saturation does not reduce the stiffness of the subgrade in the Edosaki sand and Kasumigaura sand models. However, as shown in the enlarged graph at the upper-right corner of Figure 6(b), the displacement amplitudes of the wet models have a tendency to increase with the number of loading cycles, although those of the dry models do not change or even decrease with the number of loading cycles.



(a) Permanent deformation



(b) Displacement amplitude

Figure 6 Permanent and elastic displacement of the loading surface

3.3 Final settlement of layers

After load testing, in the process of dismantling the pavement models, the geometry of each layer surface was measured by using a laser surface profiler (Figure 7). However, the shape of the subbase surface, shown in Figure 7(b), was indirectly obtained by measuring the underside surface of the base course, owing to the stickiness of base course, which made it difficult to remove the base course without disturbing the surface of the subbase course. The shape of the subgrade surface of the Kasumigaura sand models is not plotted in Figure 7(c) because the surface was disturbed while removing the subbase course.

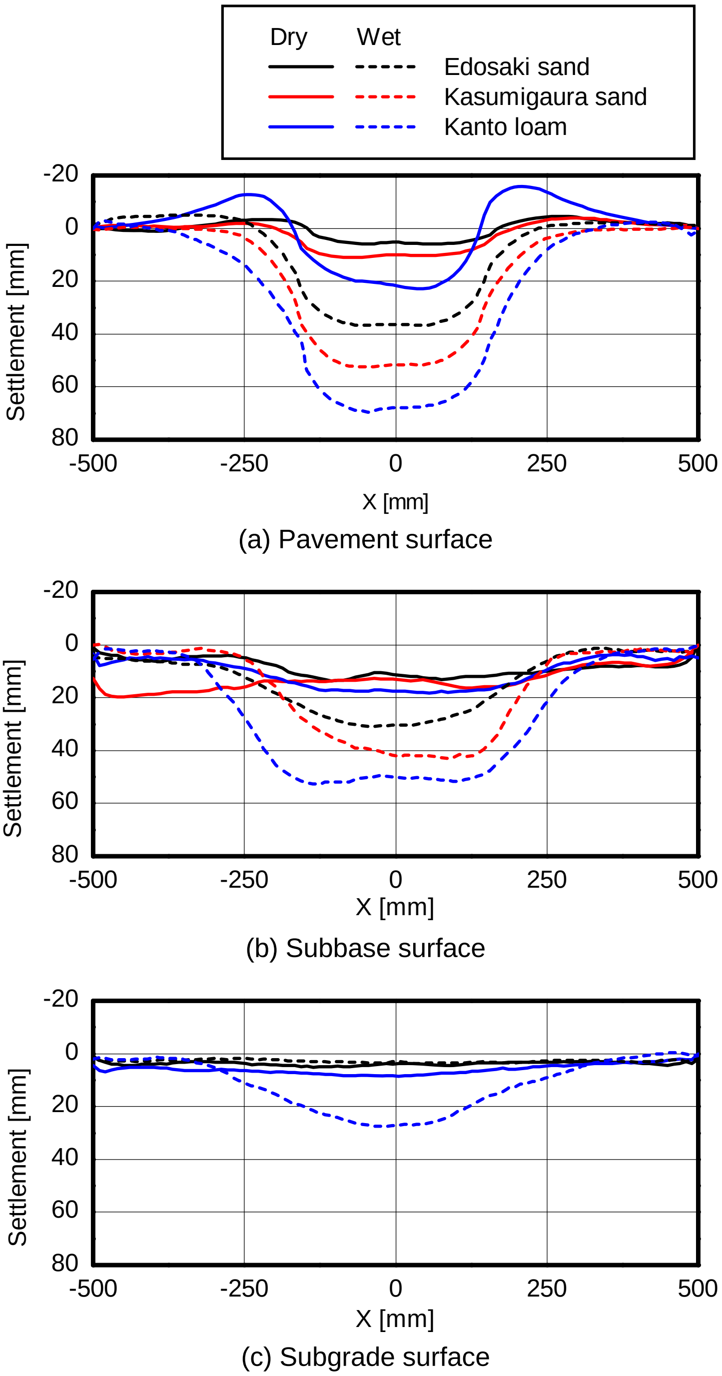


Figure 7 Settling of each layer after cyclic loading by using a laser roughness profiler

From the figure, large settlement can be seen in the Kanto loam wet and dry models. The maximum settlement of the subgrade surface of the Kanto loam model is 40 to 50% of the maximum settlement of the pavement surface. The large deformation in the case of Kanto loam could be due to the low bearing capacity of the subgrade material and the reduction of the bearing capacity due to saturation. In the case of Edosaki sand, the settling of the subgrade surface is very small, and there is a slight difference between the dry model and the wet model. Although settling of the pavement surface in the wet Edosaki sand model is significantly larger than that in the dry model, the large deformation does not reach to the subgrade material. It is deduced from this result that the large deformation in the pavement surface in the wet Edosaki sand model is due to the weakening of the subbase course by

saturation rather than the weakening of the subgrade.

Figure 8 shows the amount of compression of the subbase course calculated from Figures 7(b) and 7(c). From this figure, the maximum compression of the subbase course in Edosaki sand wet model is 80% of the maximum settlement of the pavement surface; the amount of compression in the Edosaki sand wet model is almost the same as that in the Kanto loam wet model. This means that the settlement of the pavement surface in the Edosaki sand wet model is due to the compression of the subbase course.

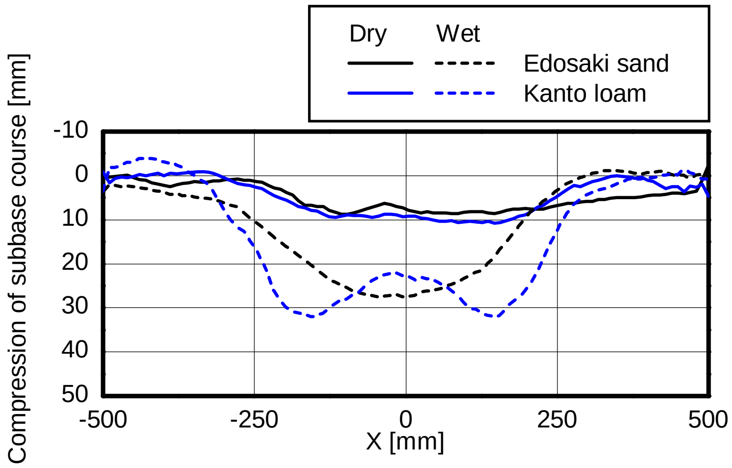


Figure 8 Compression of the subbase layer

4. CONCLUSIONS

A cyclic plate loading test on permeable pavement models was carried out to determine the influence of seepage water and repeated loading on the deformational behavior of permeable pavement roadways. Although the test parameters such as pavement thickness, saturation degree, and load condition were limited, a notable reduction in deformation resistance was observed due to the complete saturation of the subgrade and subbase materials, regardless of the type of subgrade soil. Weakening of the subgrade soil owing to the generation of excessive pore water pressure was not the cause of deterioration. Instead, the compression of the subbase course owing to diminishing permanent deformation resistance could have affected the deformational behavior of permeable pavements under conditions of high saturation. One of the reasons why serious structural damage has not been reported so far in the existing permeable pavement roadways could be attributed to the rarity of complete saturation of the roadways. Therefore, to ensure the longevity of permeable pavements, it might be effective to take the following countermeasures: 1) improve the water resistance of the subbase material, 2) install a drainage system to keep a check on the water level in the subbase layer, and 3) thicken the surface and base course to decrease the load on the subbase. In the case where subgrade soils have low permeability and low stiffness, such as Kanto loam or other cohesive soils, a combination of a high saturation degree and repeated load might affect the deformational resistance. Thickening of pavements to decrease the pressure on the subgrade surface would be effective for such soils.

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